FREQUENCY CONVERTERS FOR STARTING AND SPEED REGULATIONS OF AC MOTORS FOR TURBOMACHINE APPLICATIONS

by

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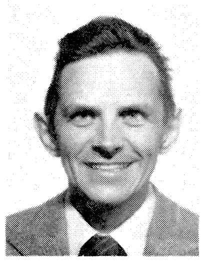

Kjell Frank received his M.S. degree in Electrical Engineering from Chalmers Technical University in Gothenburg, Sweden. He joined ASEA AB, Vasteras, Sweden, the same year. From 1965 to 1971 he worked in the Convertor Department, Development Office with responsibility mainly for frequency convertors for squirrel-cage motors and synchronous motors. From 1971-1980 he worked as the head of the same office, dealing with the development for all kinds of semiconductor convertors. From 1981 he has been the manager of the Convertor Engineering Department. Mr. Frank has been since 1976 the secretary of the International Electrotechnical Commission, Sub-Committee 22B: Semiconductor Convertors.

INTRODUCTION

The development of power semiconductors during the last 20 years has considerably increased the power handling capability of each thyristor. The main reason for this is the increase of silicon wafer area. Figure 1 is illustrating the maximum power handling capability of a six-pulse bridge (six thyristors) during the last 15 years. YST 5 means a thyristor with a cathode area of 5 cm^2 and YST 45 means a thyristor with a cathode area of 45 cm^2.

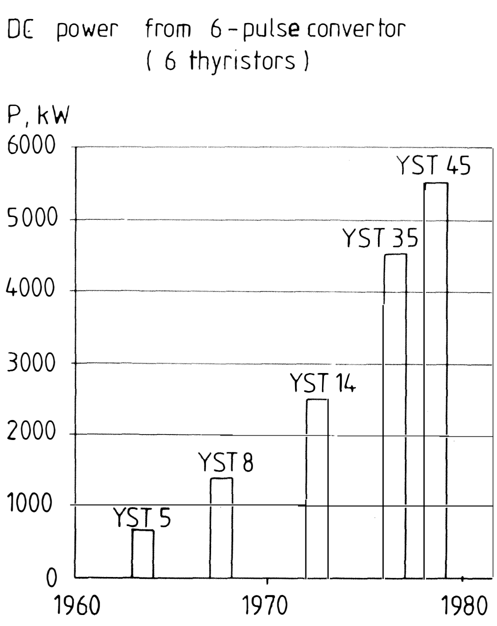

Figure 1. Development of Thyristor Power Handling Capability.

The cost of each thyristor has in no way increased proportionally to the power handling capability. If we disregard the inflation, the cost of a thyristor today is about the same as 15 years ago, while at the same time the power handling capability has increased by a factor of six. However, it has to be kept in mind that a convertor does not only consist of thyristors. Transformers, busbars, cables, reactors and capacitors are also needed to build a thyristor convertor, and these components have not experienced the same development. If we look at a complete low voltage convertor for a large DC motor drive of about 15 Mw peak power, the cost today in fixed value of money is about one-third of the cost 15 years ago.

Today thyristor convertors are built for thousands of megawatts in one single convertor station for power transmission. For motor drives the normal solution has been thyristor convertors and DC motors which have been built in the power range from a fraction of a Kw up to 20 Mw. Today is the beginning of a dramatic increase in the use of thyristor frequency convertors for AC motors in the power range 1 Kw up to 40 or 50 Mw. The thyristor and convertor technology is now not a limiting factor.

CONVERSION SCHEME

The speed of an AC motor follows the equation

$$n = 60 \cdot \frac{2\ f}{p} (1\text{-}s) \qquad (1)$$

where

n = motor speed (r/min.)
f = frequency (c/s)
p = number of poles
s = slip of the rotor (p.u.).

The survey will here concentrate on variable frequency motor drives, which means that the motor is either a squirrel-cage induction motor or a synchronous motor.

The slip of a synchronous motor during steady state operation is zero. For the squirrel-cage motor at steady state nominal torque, slip is between 3% and 0.6% for motors in the range 10Kw to 5Mw. As the number of poles is fixed (for small special motors the number of poles can be changed) for a specific motor, the frequency is the only parameter which can be changed in order to get a speed regulation of the motor.

For turbomachine applications it is generally only the type of frequency convertor equipment which is capable of giving up to or above line frequency that is of interest. The following survey is therefore limited to this type of frequency convertors.

CONVERTORS FOR SQUIRREL-CAGE INDUCTION MOTORS

The three-phase squirrel-cage motor is the most used motor for constant speed in the power range 1 Kw to 5000 Kw. The motor is very reliable and simple, with the bearings being the only parts which need maintenance. From a mechanical point of view a drawback is the need of a rather small air gap. 0.35 to 2 mm are typical values in the power range 10 Kw to 5 Mw. The need of this small air gap is due to the rotor current having to be induced from the stator, which gives the need of a very tight magnetic coupling between the stator and the rotor. With this magnetizing component in the stator current, the motor will always also have a lagging power factor, which in turn complicates the frequency convertor.

Two different types of frequency convertors for squirrel-cage motors will briefly be described. In order to keep the magnetic flux constant when the motor frequency is changed, the motor voltage also has to be changed. This is achieved in two different ways in the two schemes which will be described.

Figure 2 shows a convertor with a variable DC-link voltage. With the line-connected thyristor convertor the DC-link voltage can be controlled by adjusting the point of time in the cycle when the thyristors are gated. This variable DC voltage is smoothed in the DC-link filter consisting of a reactor and a capacitor bank. On this DC-link the inverter is connected. The inverter is "chopping" the DC voltage into an AC voltage again. As a result the motor voltage will have a waveshape according to Figure 2. The lower wave-shape is at a frequency corresponding to double that of the upper.

The voltage waveshape supplied to the motor is in principle independent of the frequency and the content of harmonics is constant compared to the fundamental. This harmonic voltage will also generate harmonic currents which in turn will generate a torque pulsation. This torque pulsation will have the frequencies 6, 12, 18 .... times the fundamental. The amplitude of the generated torque pulsation with the frequency six times the fundamental frequency will be about 10% of rated torque, and will then decrease with increasing number of order, but will be fairly independent of the load if the voltage is kept proportional to the frequency. In order to reduce the torque pulsation at low speed, the voltage could be kept at a lower value than proportional to the frequency. This is possible if the load is decreasing with decreasing frequency, which is the case for pumps, fans, and other turbomachine applications. Thus the torque pulsation can be reduced when its lowest frequency (six times fundamental) is below and around the fundamental critical frequency of the mechanical system. The torque pulsation will be damped to a much lower value on the shaft in the normal speed range for a pump, fan, or compressor.

Another solution which can be used specially for high power drives, which for this type of conversion equipment is between 0.5 Mw and 1 Mw, is to connect two of the inverters shown in Figure 2 together in a twelve-pulse connection according to Figure 3. The principal waveshape will then look

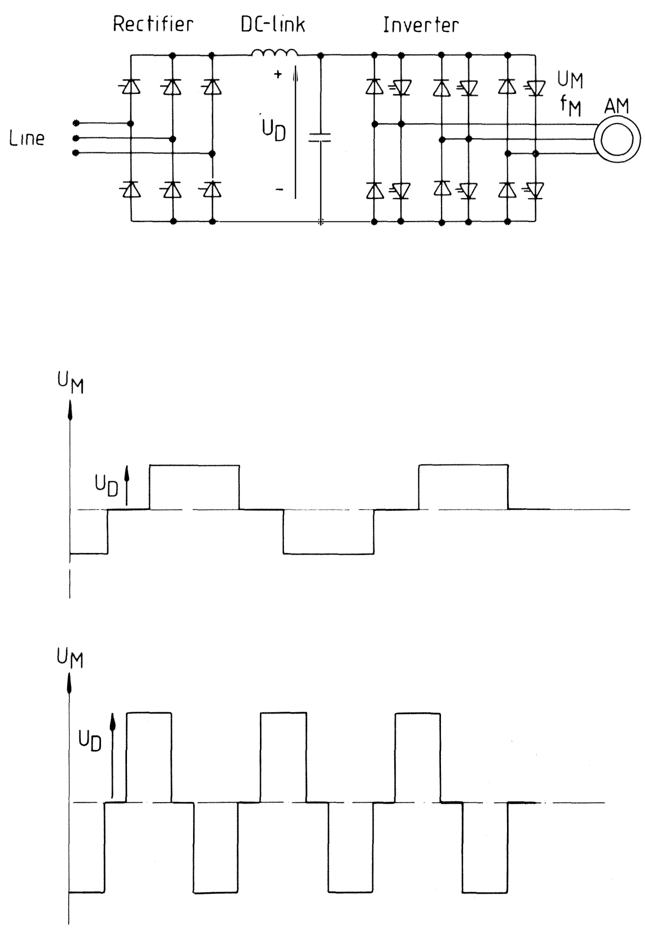

Figure 2. Frequency Convertor with Variable DC-link for Squirrel-Cage Induction Motor — Schematic and Motor Voltages at Frequency and Twice Frequency.

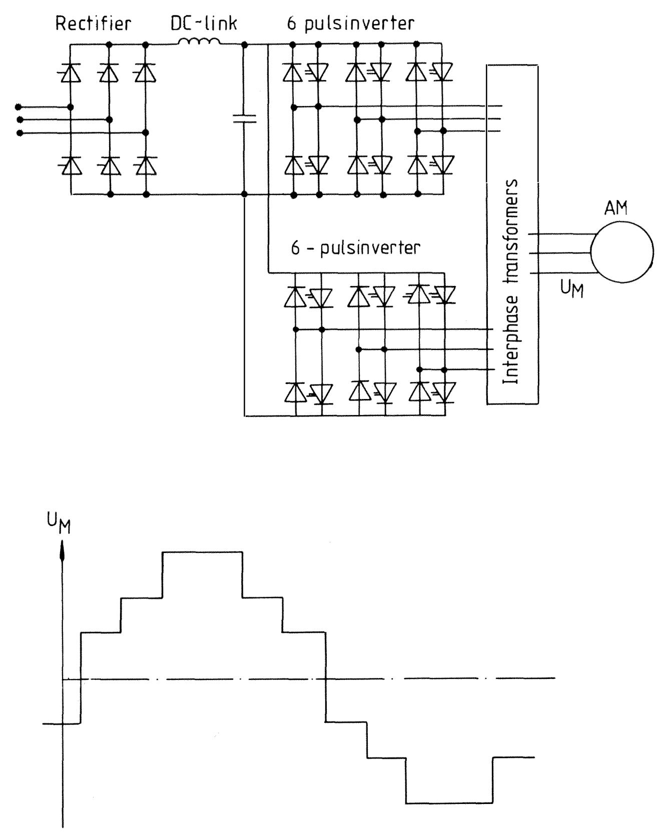

Figure 3. Frequency Convertor with Twelve-Pulse Motor Voltage — Schematic and Motor Voltage.

as shown in Figure 3. The lowest frequency of the generated torque pulsation will be twelve times the fundamental and its amplitude will only be about one percent of the rated torque for the motor. This solution has, for example, been used for internal circulation pumps in nuclear reactors, to avoid mechanical vibrations and also at very low speed.

As mentioned before, the voltage fed to the motor has to be varied over the speed range when the frequency is varied in order to control the motor speed. With a convertor scheme such as that in Figure 4, both frequency and voltage are controlled by means of the inverter part of the convertor.

The line-connected convertor is a diode rectifier which means that the DC-link voltage will be fairly constant and only varying with the line voltage. With the reactor and the capacitor bank in the DC-link, the output voltage from the rectifier is smoothed and the inverter is then "chopping" the DC voltage into an AC voltage. The big difference compared to the convertor scheme according to Figure 2 is the way the amplitude of the output voltage to the motor is controlled. As the DC-link voltage is constant, the output voltage has to be controlled by the inverter. This is achieved by the so-called PWM (Pulse Width Modulation) method.

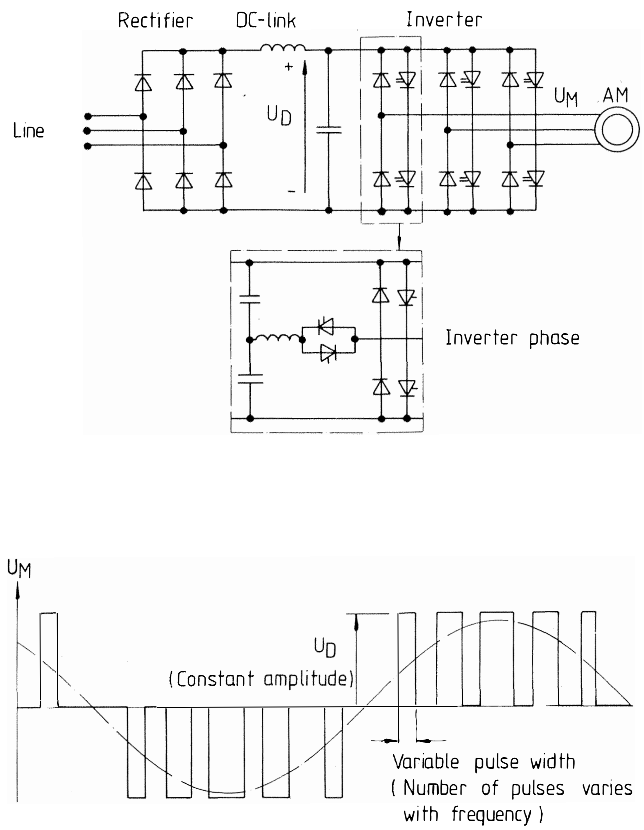

Figure 4. Frequency Convertor with Fixed DC-link for Squirrel-Cage Induction Motor (PWM-Convertor) — Schematic and Motor Voltage.

In Figure 4 an example of the waveshape is shown. Also the output voltages shown have a substantial part of harmonic voltages. By placing the pulses at the right angle and with the right width, the lower order harmonics can, however, be cancelled, which also means that the corresponding low order torque pulsation are cancelled.

As the total number of pulses per second are limited in the design of the main circuit of the inverter, the number of pulses per half period will decrease as the output frequency increases. This also means that the possibility of cancelling the harmonic voltages of the output voltage is less at a high frequency. Normally it is possible to cancel torque pulsation with frequencies lower than 150 Hz. Typical frequency spectras of the output voltage for the two different methods of voltage control are shown in Figures 5 and 6. Seen from torque quality point of views for the load of the motor, normally the PWM scheme is of some advantage, but the noise level of the motor is on the other hand a little higher with this method.

An example of the control scheme for a convertor for a squirrel-cage motor is shown in Figure 7. For turbomachine

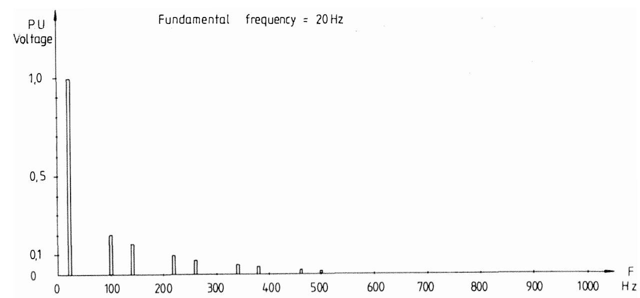

Figure 5. Calculated Frequency Spectrum in Motor Voltage for Convertor Shown in Figure 2.

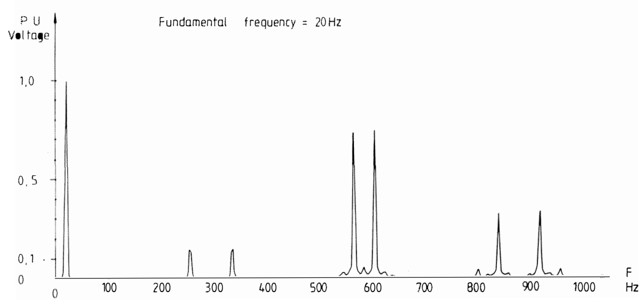

Figure 6. Measured Frequency Spectrum in Motor Voltage for PWM-Frequency Convertor.

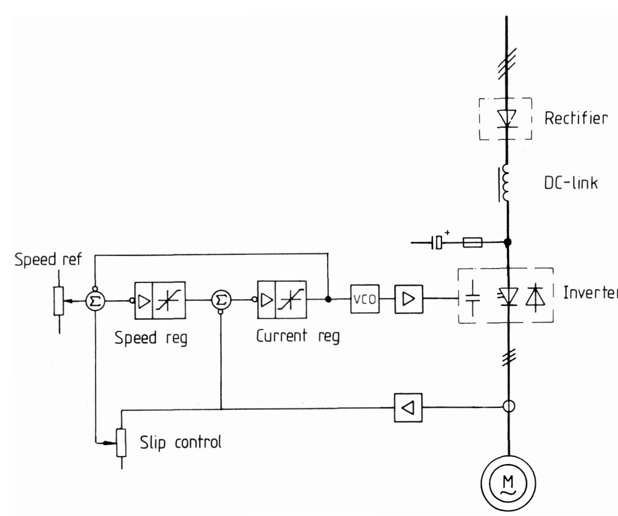

Figure 7. Principal Control Diagram for PWM-Frequency Convertor.

the steady crackling noise associated with cavitation from inadequate NPSH.

4. Surging in the suction of the pump.

Symptoms Associated with Discharge Recirculation

1. Cavitation damage to the pressure side of the vane at the discharge of the impeller.
2. Axial movement of the shaft with or without damage to the thrust bearing.
3. Cracking or failure of the impeller shrouds at the discharge of the impeller.
4. Shaft failures on the outboard end of double suction and multistage pumps.
5. Cavitation damage to the tongue or to the inlet of the diffuser vanes of the casing.

DESCRIPTION

Suction Recirculation

The reversal of the flow in the eye of the impeller at the point of suction recirculation has been observed in laboratory tests. Figure 1 shows a laboratory test arrangement of a six inch end suction pump installed in a test loop with a transparent suction pipe that permits the visual observation of the flow patterns in the impeller eye. Figure 2 shows a more detailed view of the pump with streamers attached to the inside of the transparent pipe to show the flow patterns of the vortex produced by suction recirculation. As the suction recirculation progresses down the pipe a high velocity annulus of fluid is produced at the wall while at the same time fluid is approaching and entering the eye of the impeller through the core of the annulus. The steep gradient between the flow through the core and the rotating annulus produces vortex streets that cavitate and produce random sharp crackling noise.

The vortex in the suction is the external effect of a flow reversal that is occurring at the inlet of the impeller between the vanes themselves. Between the shear face of the flow entering the impeller vanes near the hub and that ejected at the impeller eye diameter a fixed vortex is produced that travels around with the rotation of the vane system. This vortex will cavitate at its core and attack the metal surface of the pressure side of the vane in the area approximately midway

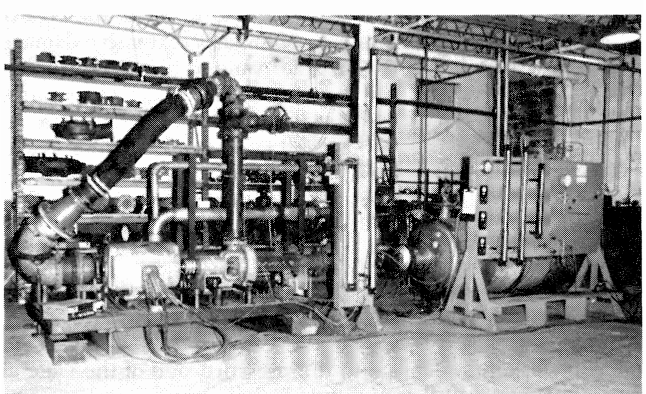

Figure 1. Laboratory Test Pump.

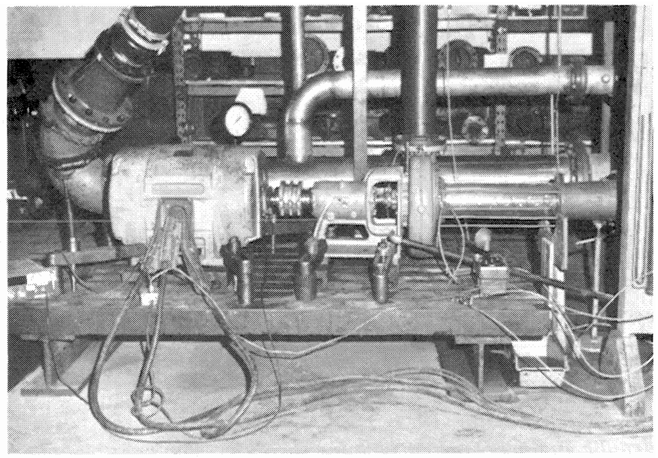

Figure 2. Laboratory Test Pump Showing Transparent Suction Pipe.

between the hub and the shroud. Figure 3 shows schematically the flow at the impeller eye during recirculation. Figure 4 shows the use of a mirror to examine the pressure or underside of the vane for suction recirculation damage. Figure 5 shows a section of a vane removed from the inlet of a large impeller heavily damaged from suction recirculation.

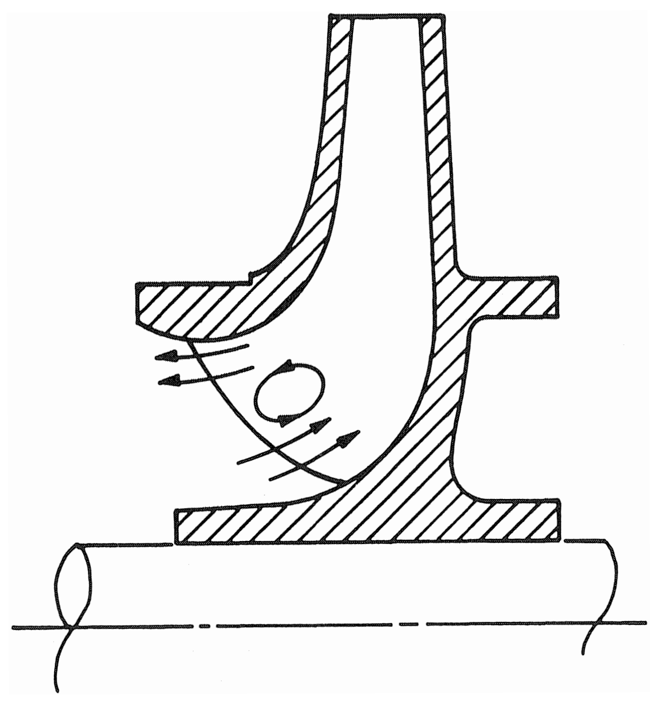

Figure 3. Suction Recirculation.

Discharge Recirculation

The reversal of flow at the discharge of the impeller is more difficult to examine directly than is the suction recirculation. One technique is to record a trace of the pressure pulsations in the discharge casing as the output flow of the pump is reduced. At some point that magnitude of the peak-to-